EXPERIMENTAL EVIDENCE FOR OPTICAL POPULATION OF THE X MINIMA IN GaAs†

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Electrons photoexcited in p^{++}-GaAs (with Cs surface monolayer) are found to "thermalize" in either the Γ or X conduction-band minima while diffusing to the surface. Two strong peaks separated by 0.3 eV of photoemitted electrons associated with these minima are observed in the energy distribution curves for 1.5 eV $\leq h\nu \leq$ 3.2 eV.

Scheer and van Laar[1] have obtained remarkably large photoemission quantum yields from vacuum-cleaved single-crystal p^{++}-GaAs covered with a monolayer of Cs. A very striking characteristic of this photoemission is the high yields in the infrared where the absorption length is quite long ($1/\alpha > 5000$ Å). Scheer and van Laar[1] suggested that due to a very small or negative effective electron affinity,[1,2] electrons optically excited deep in the GaAs are able to diffuse to the surface and escape into vacuum even though they are thermalized[3] into the lowest conduction-band minimum in the process. We have substantially reproduced their quantum yield measurements and report here energy-distribution measurements and theoretical calculations which confirm their general model; however, we have found experimentally that for $h\nu > 1.7$ eV an increasing fraction of the emitted electrons are associated with the X minima rather than Γ minimum.

Considering the exponential attenuation of light into the crystal and the diffusion of photoexcited electrons to the surface, it can easily be shown[4] that the quantum yield should be given by

$$Y(h\nu) = P/(1 + 1/\alpha L), \qquad (1)$$

where for the case of emission of thermalized carriers, P is the probability that an electron arriving at the edge of the band-bending region will escape into the vacuum, L is the diffusion length for the excited electrons, and α is the optical absorption coefficient. Using measured absorption-coefficient data from the literature, the Scheer and van Laar yield data could be fitted by taking the probability of escape P as 0.6, and the diffusion length L as ~1500 Å. The yield data we obtained can be fitted by Eq. (1) using a diffusion length of ~500 Å.

The energy distribution curves normalized to yield[5] for photoemitted electrons for various photon energies in this portion of the spectrum are shown in Fig. 1. Figure 1(a) shows the distributions from 1.4 to 2.2 eV and Fig. 1(b) from 1.8 to 3.2 eV. For photon energies from threshold (1.35 eV) to 1.6 eV, the energy distributions are practically identical, aside from magnitude, showing a single peak corresponding to a final energy of about 1.4 eV (all values of energy given are relative to the top of the valence band). At a photon energy of 1.7 eV, a higher energy shoulder begins to ap-

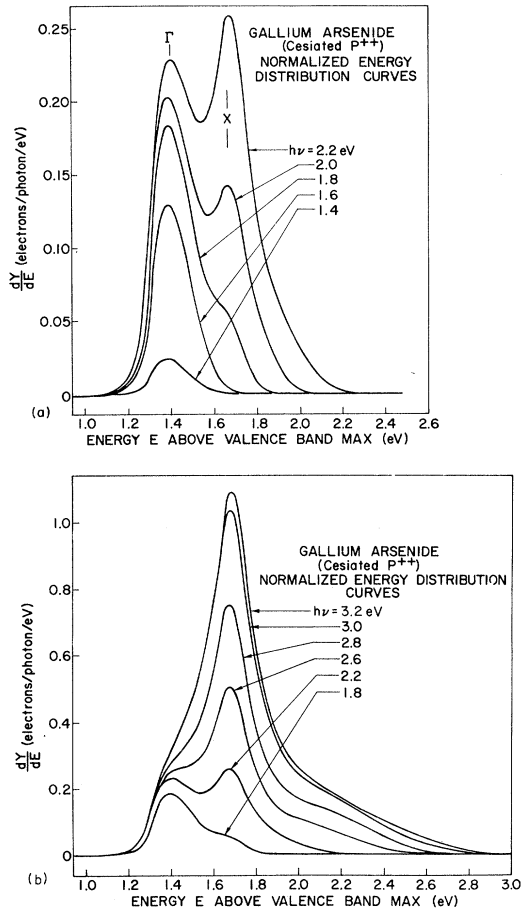

FIG. 1. Energy distributions for photoemitted electrons for photon energies between 1.4 and 3.2 eV. The distributions have been normalized to quantum yield.

pear, which develops into a clear peak at a final energy of 1.7 eV at higher photon energies. At photon energies above 2.1 eV, the higher energy peak predominates, with the high-energy peak much stronger for photon energies above 3 eV.

The explanation for this behavior in the energy distributions is shown in Fig. 2, which shows a simplified picture of the electronic band structure of GaAs (effects of spin-orbit splitting in the valence band are now shown and only the lowest conduction band is included).[6] For photon energies below 1.7 eV, excitation-escape process is illustrated by the arrow labeled (a) in Fig. 2. The electrons are excited to the region of the Γ conduction-band minimum and they are thermalized in that minimum, giving rise to the 1.4-eV peak of emitted electrons. At photon energies above 1.7 eV, however, an additional process, marked (b) in the figure, can occur. In this process the electron is again excited to the region near Γ, but is then scattered into the vicinity of the X conduction-band minima and "thermalized" there. The 1.7-eV peak reflects this accumulation of electrons in the X minima. The 1.7-eV peak grows with increasing photon energy despite the fact that the electrons are not directly excited into the X minima for $h\nu \leq 3.2$ eV Rather, they are being excited into higher energy states.[6,7] Future work will be directed at obtaining more detailed information on the scattering events involved here. There is no clear sign of transitions to the L minima in the data. Considering the fact that strong scattering of electrons from the L minima to the lower lying high densities of states associated with the X minima would discourage the accumulation of electrons in the L minima, this is perhaps not surprising.

In summary, these measurements indicate that the high quantum yields observed for cesiated p^{++}-GaAs in the threshold region are indeed due to the emission of thermalized electrons which have diffused to the surface; however, it is found that the photoexcited electrons may be thermalized in either the Γ minimum or X minima of the conduction band. This allows for the location of the X minima approximately 0.3 eV above the Γ minimum. The implications from the absolute yield and the number of electrons that appear in each peak of the energy distributions is that the "diffusion length" of electrons in each sub-band is comparable and is of the order of 10^{-5} cm in this work. The relevance of this work to the complete understanding of the Gunn effect is recognized and future work will be directed towards a fuller understanding of aspects directly related to the Gunn effect and other phenomena related to the population of higher lying conduction-band minima.

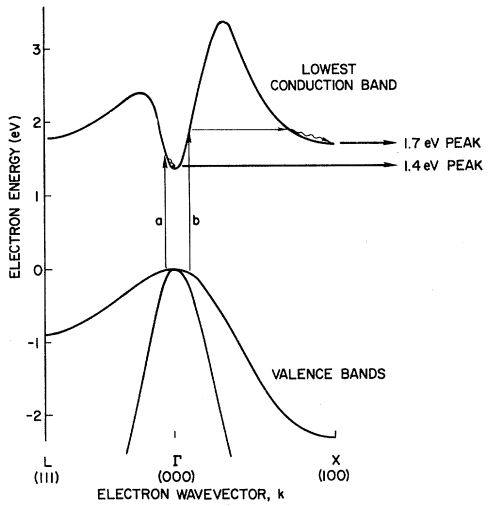

FIG. 2. Schematic of the GaAs band structure near the energy gap showing the relevant excitation-escape processes. For photon energies below 1.7 eV, the electrons thermalize in the Γ minimum before escaping into vacuum, while for larger photon energies, an increasing number "thermalize" in the X minima.

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[1]J. J. Scheer and J. van Laar, Solid State Commun. 3, 189 (1965).

[2]The small negative effective electron affinity is due to the combined effect of the low (~1.4 eV) electron affinity of GaAs with a monolayer of Cs and the band bending at the surface due to the n^{--} surface produced by the Cs on the p^{++}-GaAs. Because of the high p doping level of the bulk and the surface Cs n^{--} doping, the band bending takes place within approximately 50 Å of the surface. Thus, for greater distances from the surface the Γ minimum lies approximately at vacuum level.

[3]Since the energy resolution in the energy-distribution measurements is not sufficient to resolve structure of thermal widths, the term "thermalized" as used here indicates distributions which are found to have been thermalized within the accuracy of our measurement.

[4]J. L. Moll, Stanford Electronics Laboratories Quarterly Report No. 2, SEL-66-075, Stanford, California 94305 (unpublished).

[5]The yield has been corrected for reflection so that it is in terms of electrons per photon absorbed.

[6]The general features of this band structure are taken from the work of M. L. Cohen and T. K. Bergstresser, Phys. Rev. 141, 789 (1966).

[7]M. L. Cohen and J. C. Phillips, Phys. Rev. 139, A912 (1965).

POLARON EFFECTS IN THE CYCLOTRON-RESONANCE ABSORPTION OF InSb

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Comparison of experimental results for cyclotron-resonance measurements above and below the Reststrahl frequency reveals anomalies attributable to polarons.

We have observed a discontinuity in the magnetic-field dependence of the cyclotron-resonance energy in InSb which can be attributed to polaron effects. Because the transitions studied in the present experiment are between conduction-band Landau levels, the polaron theory developed earlier[1] can be expected to apply directly and quantitatively to the data. In contrast, quantitative interpretation of the interband magnetoabsorption data obtained previously[2] is complicated by valence-band and exciton effects. Our present data, however, confirm the essential correctness of attributing the interband anomalies to polaron effects and constitute the first direct observation of polaron effects on Landau levels.

It has been previously suggested[3] that the experimental investigation of cyclotron resonance in polar materials for frequencies above and below the Reststrahl frequency could be expected to show characteristic self-energy effects associated with the electron–LO-phonon interaction. Our recent theoretical examination of the polaron in a magnetic field has shown that (1) the experimental cyclotron-resonance energy, $h\nu_{CR1}$, which is a linear function of magnetic field at low fields, should saturate at the value of the LO phonon energy, $\hbar\omega_0$, as the magnetic field increases; (2) a second resonance, whose energy, $h\nu_{CR2}$, is never less than $\hbar\omega_0$, should appear at higher magnetic fields; (3) $h\nu_{CR2}$ should lie above the position expected from the extrapolation of $h\nu_{CR1}$ from the low-field region.

Experimentally, we have examined the variation with magnetic field of the cyclotron-resonance energy of electrons in InSb for photon energies above and below $\hbar\omega_0$. The separation of $h\nu_{CR2}$ from the extrapolation of $h\nu_{CR1}$ is clarly demonstrated. In addition, our measurements are consistent with predictions (1) and (2) above. The observation of cyclotron resonance for photon energies arbitrarily close to $\hbar\omega_0$ is hindered greatly by lattice absorption. The results of the present experiment are consistent with our previous study of the corresponding energy levels using interband magnetoabsorption,[1,2] where the lattice absorption problem does not arise. The latter results show more clearly effects corresponding to (1) and (2) but contain complications due to excitons and to valence band behavior.

Consider the predictions of Fröhlich's polaron theory. The energy of a conduction electron in the presence of weak coupling to the longitudinal optical phonons and in the limit of small k can be calculated using simple perturbation theory and is given by[4]

$$E \approx \frac{\hbar^2 k^2}{2m_e}\left(1-\frac{\alpha}{6}\right)-\alpha\hbar\omega_0, \qquad (1)$$

where m_e is the electron effective mass, and α is the coupling constant (defined in Ref. 4) with characterizes the strength of the interaction. Polaron effects show up as an increase in effective mass by the factor $(1+\alpha/6)$ and a downward shift of the energy levels by an amount $\alpha\hbar\omega_0$. For InSb the former effect would be quite small (increasing the band mass by $<0.5\%$) and $\alpha\hbar\omega_0 \approx 0.02\times 24 \approx 0.5$ meV. In the absence of much more accurate knowledge of the rigid-lattice band structure than is presently available, these effects could not be ver-